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Title: **OPTICAL COUPLER AND AWG HAVING THE SAME**

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Les documents fixés à cette attestation sont conformes à la version initialement déposée de la demande de brevet européen spécifiée à la page suivante.

Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

01204779.1

Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

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Blatt 2 der Bescheinigung
Sheet 2 of the certificate
Page 2 de l'attestation

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Optical coupler and AWG comprising the same

The invention pertains to an optical coupler comprising at least one input waveguide, a coupling region, and a plurality of output waveguides.

US patent 5,136,671 is directed to an NxN integrated optical interconnection apparatus comprising two such couplers, in this case so-called star couplers. In the description of US 5,136,671, it is explained that optical switching, multiplexing, and de-multiplexing have been accomplished in the past by using an interconnection apparatus having a plurality of closely spaced input waveguides communicating with the input of a star coupler. The output of the star coupler communicates with an optical grating comprising a series of optical waveguides, each of the waveguides differing in length with respect to its nearest neighbour by a predetermined fixed amount. The grating is connected to the input of a second star coupler, the outputs of which form the outputs of the switching, multiplexing, and de-multiplexing apparatus.

It is recognised in US 5,136,671 that, in order to achieve high efficiency power transfer between a relatively large number of input ports and a relatively large number of output ports, the input and output waveguides connected to the star couplers must be closely spaced in the vicinity of the star couplers. This causes a significant degree of mutual coupling between those adjacent input and output waveguides, producing increased undesirable cross-talk between the channels of the device and decreased efficiency in transferring optical power from the selected input ports to selected output ports of the apparatus.

The star couplers described in US 5,136,671 comprise a dielectric slab which forms a free space region having two curved, preferably circular, boundaries. The input waveguides and the waveguides in the grating are

connected to the free space region in a substantially uniform fashion along the boundaries.

US patent 4,786,131 is directed to an MxN (star) coupler comprising a planar waveguide having a pair of opposed edges that serve as entrance and exit facets "for introducing and extracting electromagnetic radiation from said waveguide". The planar waveguide is structured to confine the radiation propagating therein in a single mode in its depths without confining it in its width so that, in its width, radiation propagates as an expanding wavefront.

Although the phase distribution at the output plane of the star couplers according to these prior art documents can be adequately matched to the output waveguides, the amplitude distribution cannot. As a result of such amplitude mismatch, a considerable amount of the electromagnetic radiation will be coupled in the areas between the output waveguides, in turn resulting in insertion losses and additional cross-talk, especially when applied in arrayed waveguide gratings.

It is an object of the present invention to provide an improved optical coupler, wherein the amplitude distribution can be matched more accurately to the output waveguides.

To this end, the coupler according to the first paragraph is characterised in that the coupling region comprises a plurality of coupled waveguides, which, over at least part of their lengths, diverge with respect to each other in the propagation direction of electromagnetic radiation launched in the said input waveguide.

It is preferred that also the width of at least some of the waveguides in the coupling region increases, preferably gradually, and/or that the width of the gaps between the waveguides in the coupling region is at least substantially constant.

As will be explained below, coupling between the waveguides is enhanced considerably if at least some of the waveguides in the coupling region comprise a section having a width that is less than the critical width of the waveguide at the wavelength(s) at which the coupler is designed to operate.

In a further preferred embodiment the centre lines of at least some of the gaps between the waveguides in the coupling region follow the lines of a Gaussian diffraction pattern in accordance with the following set of equations (E1) or a linearised version thereof:

$$w(z) = w_k\sqrt{1+(\alpha z)^2} \quad ; \quad \alpha = \frac{(\lambda / n_{eff})}{\pi w_o^{\ 2}} \quad ; \quad R = z\left(1+\left(\frac{1}{\alpha z}\right)^2\right) \qquad \text{E1}$$

where z is the longitudinal propagation position; $w(z)$ is the z-dependent lateral position of the central line of the k^{th} gap; w_k is the position of the centre of the k^{th} gap at $z=0$; w_o is the beam waist at $z=0$; λ is the wavelength in vacuum, n_{eff} is the effective index and R is the radius of curvature of the phase front.

In a coupler designed using equations E1, the sum of the widths of the waveguides and gaps, gradually increases in the propagation direction and insertion loss and cross-talk are further reduced.

The amplitude distribution and, hence the distribution of power, over the output waveguides can be further modified, e.g. equalised so as to obtain a very effective power coupler, by adjusting the positions, in the propagation direction, where centre lines of the gaps between the waveguides in the coupling region start to follow the lines of a diffraction pattern. This is preferably done by means of the following set of equations (E2) or a linearised version thereof:

$$w(z)=\begin{cases} w_k & \text{, for } z < z_k \\ w_k\sqrt{1+\left[\alpha(z-z_k)\right]^2} & \text{, for } z <= z_k \end{cases} \quad ; \quad \alpha=\frac{(\lambda/n_{eff})}{\pi w_o^{\ 2}} \qquad \text{E2}$$

Thus, strong coupling between adjacent waveguides in the inner part of the coupling region is ensured. The outer waveguides widen gradually, thereby collecting the light entering from the inner part of the coupling region.

In an especially preferred embodiment, the coupler, when electromagnetic radiation of a wavelength at which the coupler is designed to operate is launched in one of the inputs, generates an amplitude distribution, which exhibits, in a lateral direction, a plurality of peeks and wherein the output waveguides are positioned at the lateral positions of these peaks. Thus, the amount of radiation coupling into the gaps between the waveguides as well as cross-talk are further reduced.

In general, it is preferred that all the above-mentioned waveguides in the coupler according to the present invention are planar waveguides.

The invention also pertains to an Arrayed Waveguide Grating (AWG), also known as *inter alia* Phasar, Phaseur, and Waveguide Grating Router, comprising the present coupler. The advantages of the coupler are especially noticeable in AWGs, since even small deviations from the amplitude and phase distributions for which such a device was designed result in substantial losses or render it inoperative all together.

For the sake of completeness, it is noted that European patent application 0 717 295 discloses an MxO multiplex/de-multiplex device comprising two evanescent wave couplers each comprising an array of fused optical fibres. The phase distribution at the output of such couplers does not describe a circular or elliptic phase front, which are therefore less suitable for use in AWGs. This is especially

true for wavelength de-multiplexers designed to operate at a broad wavelength range.

The invention will now be explained in more detail with reference to the drawings in which several preferred embodiments are schematically shown.

Figures 1A and 1B show a cross-section of a typical waveguide structure respectively of a mode propagating therein.

Figures 2A to 2C illustrate the effects of the width of a waveguide on the effective width of a mode propagating therein.

Figure 3 shows a top view and corresponding cross-section of a first embodiment of the coupler according to the present invention.

Figure 4 shows a top view and corresponding cross-sections of a coupling region suitable for use in the coupler according to figure 3.

Figures 5A and 5B show an amplitude distribution generated by respectively a prior art coupler and a coupler according to the present invention.

Figure 6 shows a cross-section and a top plan view of a second embodiment according to the present invention.

Figure 7 shows a top plan view and corresponding cross-sections of a third embodiment according to the present invention.

An example of a typical waveguide structure 1 is shown in figure 1A and comprises a substrate 2 and a top layer 3 of InP (having a refractive index of n=3.17) sandwiching a core layer 4 of InGaAsP (having a refractive index of n=3.39). Other types of materials, e.g. silica on silicon (SiO2/Si), siliconoxintride (SiON), silicon on insulator (SOI), and polymers, are equally suitable. The top surface of the top layer 2 exhibits a ridge 5, which causes a lower energy state region in the structure and thus defines a quantum well, i.e. in this case an optical

waveguide. Launching electromagnetic radiation having a wavelength of e.g. 1.5 μm in the waveguide results in a mode having a field distribution as shown in figure 1B.

Further, figures 2A to 2C illustrate a phenomenon that is advantageously employed in the preferred embodiments of the present invention. In a very wide waveguide (figure 2A), the effective field width, w_{eff}, of a mode propagating in the waveguide substantially corresponds to the width, w, of the said waveguide. The effective field width decreases with a decreasing width of the waveguide (figure 2B) down to and including the critical width of the waveguide. Beyond the critical width (figure 2C), the effective field width of the mode increases considerably which, in case of a plurality of closely spaced waveguides, results in a strong coupling of the said waveguides. The field profile of the entire structure can no longer be described by the sum of the individual modal field profiles, but has to be constructed as the sum of fields of the so-called supermodes of the total waveguide structure.

It is noted that, within the framework of the invention, the effective field width is defined as being equal to twice the distance from the centre of the mode to the lateral position where the amplitude of the mode has dropped to a value equal to the amplitude at the centre of the mode divided by e (≈ 2.7183). The above-mentioned critical width of a waveguide is dependent on the index contrast of the waveguide at the wavelength or wavelength range at which it was designed to operate and is defined as the width where the width of the mode propagating therein is at a minimum.

Figure 3 shows a first preferred embodiment according to the present invention comprising a plurality of single-mode (SM) or multi-mode (MM) input waveguides 6, a multi-mode (MM) coupling region 7, of which an example is shown in more detail in figure 4, and a plurality of single-

mode or multi-mode output waveguides 8. The input waveguides 6 (in region A) are de-coupled and converge towards an input plane 9 of the coupling region (B). The coupling region according to figure 4 comprises waveguides 10, each having a first portion 11, which converges from the input plane 9 towards a transition (sub-region D), and a second portion 12, which diverges towards a circular output plane 13 (dotted line in figure 3). At this output plane 13, the said second portions 12 are connected to the output waveguides 8.

Further, the first portions 11 all have a constant width ('w_2' on the right-hand side of figure 4) that is less than the critical width at the wavelength at which the coupler is designed to operate, in this case 1.5 μm. At the transition, the width of each of the first portions 11 of the waveguides 10 is substantially equal to the width (w_1) of the gaps, resulting in the sum of supermodes mentioned above.

The gaps between the second portions 12 are of constant width (w_1) and follow centre lines calculated by a linearised version of equations E1 mentioned above. Accordingly, the width (w_2) of each of the second portions 12 of the waveguides 10 increases gradually, initially to a width larger than the critical width and after that to a width equal to that of its respective output waveguide 8. As a result, the waveguides 10 are gradually de-coupled.

As the said widths w_1, w_2, need not be in excess of e.g. 1 μm, the manufacture of the coupler in hand does not require extreme lithographic resolutions and thus can be manufactured by means of a conventional and relatively straightforward lithographic process.

A simulation using the Beam Propagation Method (BPM) was carried out for a prior art star coupler and for the coupler according to figures 3 and 4 discussed above. Figures 5A (prior art) and 5B (invention) depict the respective amplitude distributions at the output planes of

the couplers. Figure 5A shows a smooth distribution, whereas figure 5B shows a distribution having several peaks. These peaks are in register with the output waveguides 8, i.e. the amplitude is high where the coupling region is connected to the output waveguides and low at the locations of the gaps between the output waveguides 8 where losses are likely to occur.

Figure 6 shows part of an alternative to the coupling region shown in figure 4. The converging first portions (not shown) of the waveguides in the coupling region are substantially identical to those in the coupler according to figure 4. However, the centre lines of the diverging second sections were calculated by means equations E2 cited above. As a result, the waveguides initially run straight over a distance, which is largest for the centre waveguide and smaller towards the edges of the coupling region and, in turn, the amplitude distribution at the output plane flattens and power is distributed more evenly over the outputs.

Figure 7 shows a third preferred embodiment according to the present invention, which comprises high contrast input and output waveguides. The high contrast inputs (A) are coupled directly into the coupling region (B), which itself is similar to that shown in figure 3. For the high contrast output waveguides (E), it is preferred that transitional sections are provided, which each comprise a (relatively broad) low confinement section (C) and a matched high confinement tapered section (D) which is coupled to a respective output waveguide.

From the above explanations, it will be clear that in the optical couplers according to the present invention both the amplitude distribution and a phase distribution, at least at the output plane, can be adjusted to accurately match the output waveguides and thus to operate at relatively low loss and cross-talk.

The invention is not restricted to the above-described embodiments, which can be varied in a number of ways within the scope of the claims.

CLAIMS

1. Optical coupler comprising at least one input waveguide, a coupling region, and a plurality of output waveguides, **characterised in that** the coupling region comprises a plurality of coupled waveguides, which, over at least part of their lengths, diverge with respect to each other in the propagation direction of electromagnetic radiation launched in the said input waveguide.

2. Optical coupler according to claim 1, wherein the width of at least some of the waveguides in the coupling region increases.

3. Optical coupler according to claim 1 or 2, wherein the width of the gaps between the waveguides in the coupling region is at least substantially constant.

4. Optical coupler according to any one of the preceding claims, wherein at least some of the waveguides comprise a section having a width that is less than the critical width of the waveguide at the wavelength(s) at which the coupler is designed to operate.

5. Optical coupler according to any one of the preceding claims, wherein the centre lines of at least some of the gaps between the waveguides in the coupling region follow the lines of a Gaussian field in accordance with equations E1 in the description or a linearised version thereof.

6. Optical coupler according to any one of the claims 1 to 5, wherein the centre lines of the gaps between the waveguides in the coupling region follow the lines of a field in accordance with equations E2 in the description a linearised version of those lines.

7. Optical coupler according to any one of the preceding claims, wherein the waveguides initially converge in the propagation direction and subsequently diverge.

8. Optical coupler according to any one of the preceding claims, wherein the coupler, when electromagnetic radiation of a wavelength at which the coupler is designed to operate is launched in one of the inputs, generates (an end field with) an amplitude distribution, which exhibits, in a lateral direction, a plurality of peeks and wherein (the beginning of) the output waveguides are positioned at the lateral positions of these peaks.

9. Optical coupler according to any one of the preceding claims, wherein the all the said waveguides are planar waveguides.

10. Arrayed waveguide grating comprising at least one optical coupler according to any one of the preceding claims.

ABSTRACT

The invention pertains to an optical coupler comprising at least one input waveguide, a coupling region, and a plurality of output waveguides. The coupling region comprises a plurality of coupled waveguides, which diverge with respect to each other in the propagation direction of electromagnetic radiation launched in the said input waveguide. In these couplers, both the amplitude distribution and a phase distribution can be accurately matched the output waveguides resulting in relatively low loss and cross-talk.

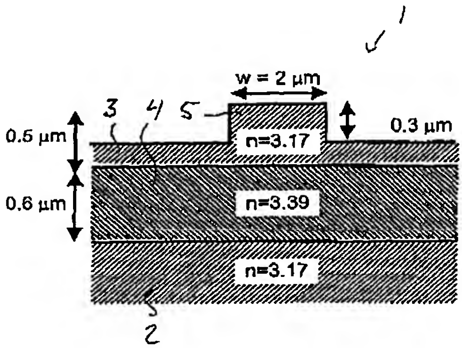

fig. 1A

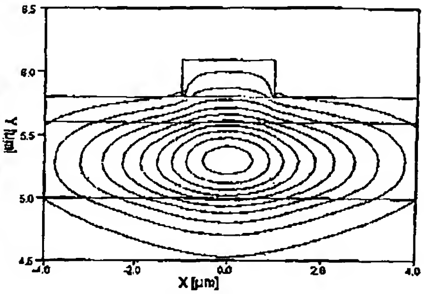

fig. 1B

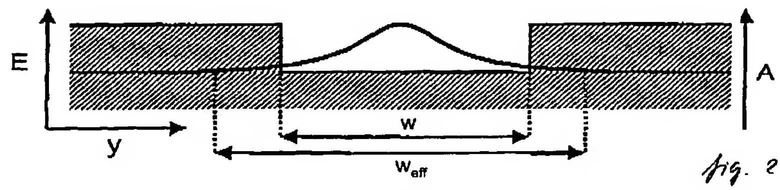

fig. 2A

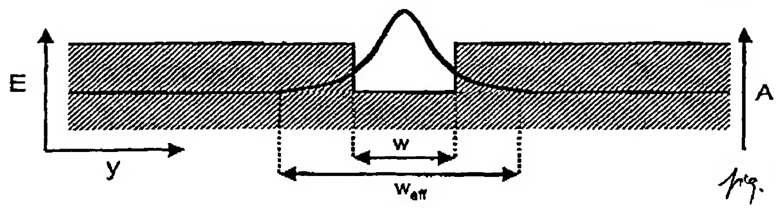

fig. 2B

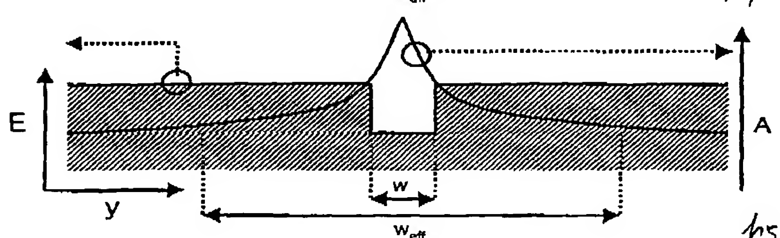

fig. 2C

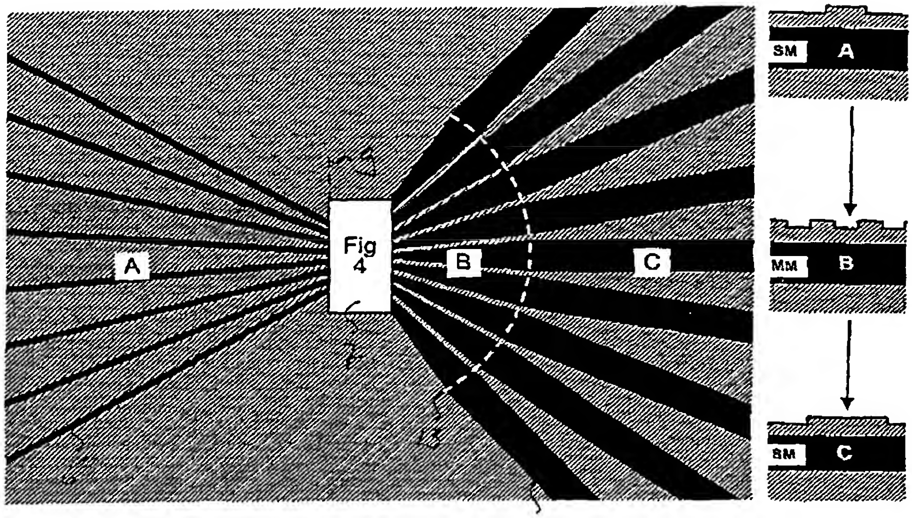

fig. 3

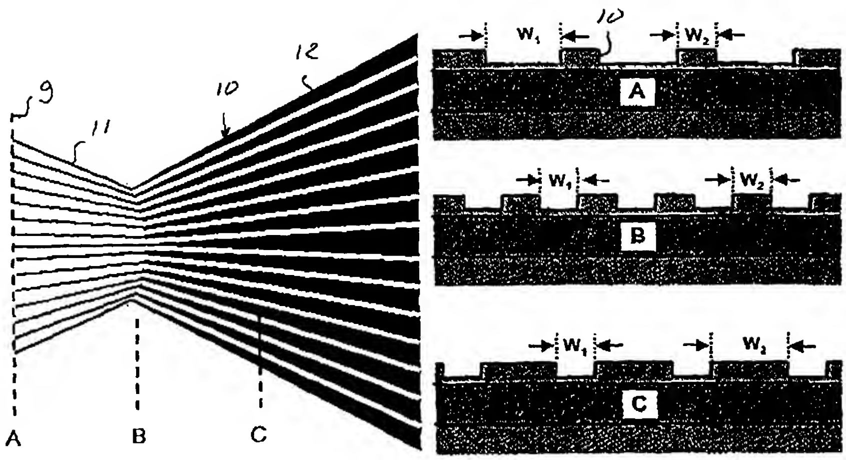

fig. 4

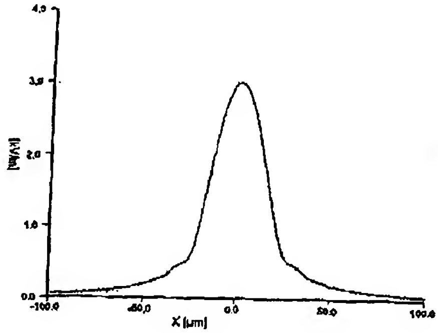

fig. 5A

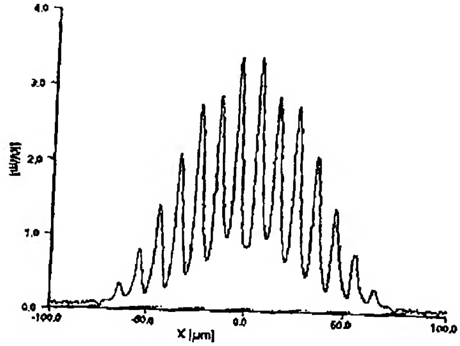

fig. 5B

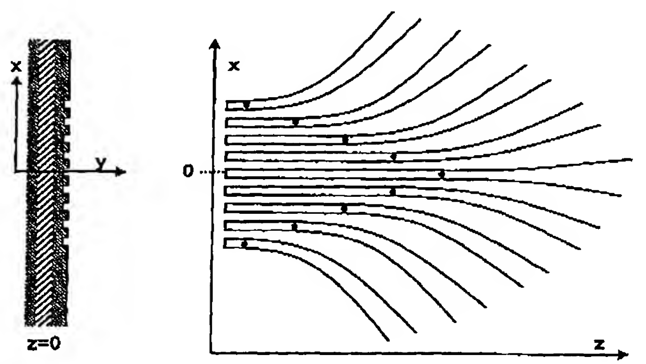

fig. 6

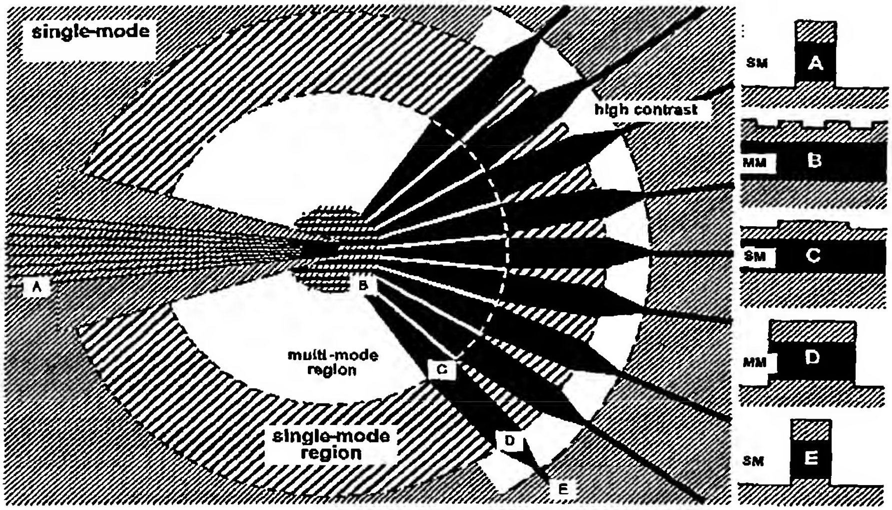
single-mode
high contrast
A
B
multi-mode region
C
single-mode region
D
E
SM
A
MM
B
SM
C
MM
D
SM
E

Fig. 7